# Nitride Quantum Wells and Photonic Structures

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## *Photonic Crystals Brighten Nitride UV Emitters*

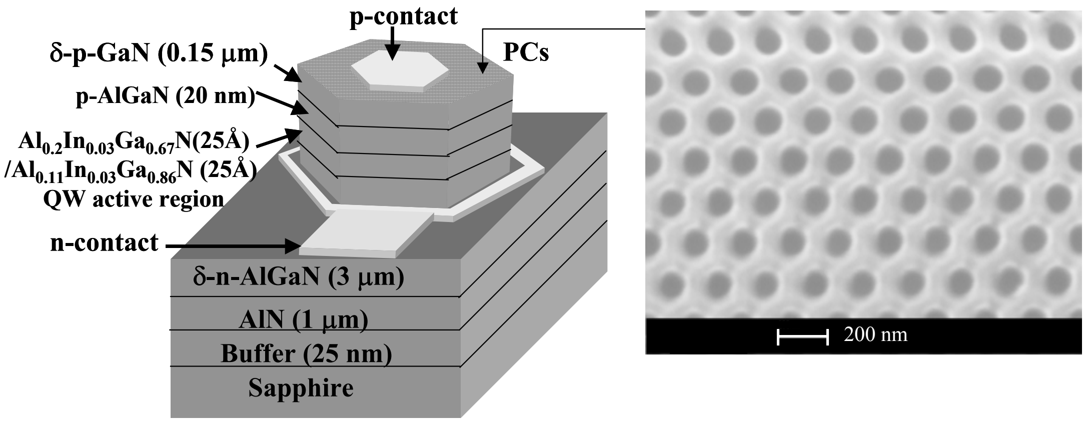


Fig. 1 Schematic of photonic crystal (PC) incorporation on III-nitride emitters and scanning electron microscopy (SEM) image of PCs created by nanofabrication.

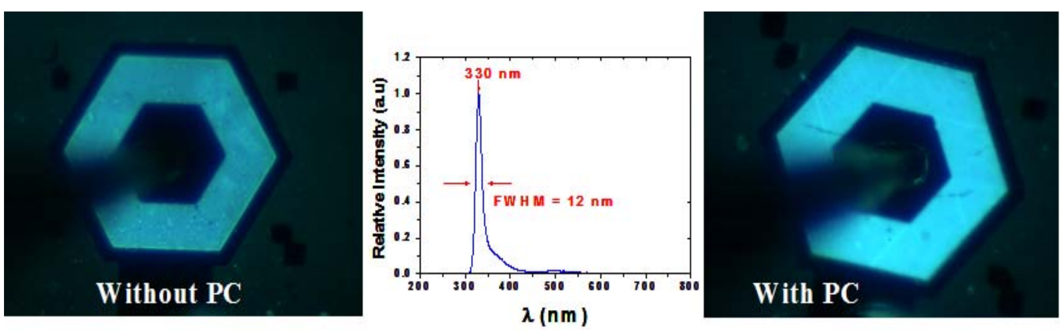


Fig. 2 Optical microscopy images of 330 nm UV LEDs in action (top view). The output power enhancement is visible in the LED with PCs and is about 3 times higher than in the conventional LED without PCs.

- We have achieved nanofabrication of photonic crystals (PCs) on III-nitride UV emitters (Fig. 1). Under optical pumping, an unprecedented enhancement factor of 20 in emission light intensity was achieved. Current injected UV emitters with PCs show an enhancement factor of 3 times over conventional emitters (Fig. 2).
- Further enhancement in extraction efficiency in III-nitride UV emitters using PCs will be realized with additional advances in the material quality and device processing particularly in the following areas: (a) improving the conductivities of n- and p-type AlGaN layers to allow a more effective current injection and spreading, (b) increasing etch depth of air holes to ensure penetration into the active layers, and (c) fabricating PCs with reduced diameter/periodicity to be tuned to match the photonic band gap.

Research results:

Multiple scattering of photons by lattices of periodically varying refractive indices in the PCs acts to form photonic bandgaps (PBGs) in which propagation of certain wavelengths of the electromagnetic waves are prohibited. This can be exploited to control as well as enhance spontaneous emission and/or light extraction efficiency in a variety of active and passive optoelectronic devices including LEDs. Ideal PBG is achieved by periodicity in 3 dimensions but for extraction of light in LEDs, it is sufficient to eliminate light propagation only in the horizontal plane with the use of 2-D PCs. For this purpose, triangle lattice of air holes in a dielectric background are shown to be one of the most prominent 2-D structures to present PBGs and are typically etched into semiconductor materials. The enhancement of external efficiency of LEDs using PCs has been studied mainly in the infrared (IR) wavelength regions. Most of the previous studies have been carried out using optical pumping on semiconductor materials not yet fabricated into electrically pumped LED devices and therefore lacked electrical data, which is essential in characterizing LEDs.

The incorporation of PCs into III-nitride UV/blue emitters offers a solution for improving the extraction efficiency, but is very challenging. This is due in part to the difficulty in fabrication associated with the nanometer-scale features required for blue and UV wavelengths. Nitride LEDs are generally grown on insulating sapphire substrates, which makes electron-beam (e-beam) lithography patterning of nano-scale holes difficult (due to charge accumulation). One other challenge is the ability to transfer the designed patterns from e-beam resist to the samples. Because the III-nitrides are hard materials, the most effective method to achieve this is by high-density plasma etching. This requires an optimized resist or a lift-off material that will withstand the plasma etching as well as maintain the small features of the PCs.

We grew III-nitride LED structures by metalorganic chemical vapor deposition (MOCVD). We inserted high quality AlN epilayer as a template and incorporated Si and Mg-delta-doping schemes (developed under NSF support) into the UV LED structures to reduce dislocation density and improve the n- and p-type conductivities. The active region was a single QW consisting of $Al_{0.11}In_{0.03}Ga_{0.86}N/Al_{0.2}In_{0.03}Ga_{0.77}N$ layer for UV (330 nm) LEDs. The active region was sandwiched between Si and Mg-$\delta$-doped AlGaN epilayers. We also grew blue (460 nm) LEDs using $In_{0.2}Ga_{0.8}N/GaN$ QW as the active region for comparison studies.

We have incorporated 2-D PCs into real devices with triangular lattice patterns of circular holes with varying diameter/periodicity down to 100/180 nm by e-beam lithography and inductively coupled plasma dry etching (ICP). To provide a reference, other sample devices did not receive the PC treatment. We first performed optical characterization using near-field scanning optical microscopy (NSOM) uniquely configured for UV wavelengths and the results showed a 60 degree periodic variation with the angle between the propagation direction of emission light and the PCs lattice, which confirmed the effect of PCs. We achieved a 20-fold enhancement of light extraction using optical pumping and a 3-fold enhancement in light extraction by electrical pumping in both blue and UV LEDs. Because the formation of PCs reduced lateral guided modes, the result is a significant enhancement of light extraction in the vertical direction due to coupling into free space. Much work remains to be done to further enhance the extraction efficiency of deep UV emitters (under current injection) by utilizing PCs.

The results were published in Applied Physics Letters [83, 1231 (2003); 84, 466 (2004); 85, 142 (2004)] and presented in an invited talk by the Co-PI in the American Physical Society 2004 March Meeting (Montreal) [Focused Session on “Wide Bandgap Semiconductors”]. The PI has been invited to present nitride PC work in *2005 International Symposium on Contemporary Photonics Technology* to be held in Tokyo (January 2005) and in *CLEO 2005* to be held in Baltimore (May 2005). *Our NSF supported work on nitride PCs was also reported by the January 2004 issue of Photonic Spectra, February 2004 issue of SPIE’s oemagazine, March 2004 issue of Compound Semiconductors, and March issue 2004 of III-V Reviews.*

Significance of this work:

Our NSF supported research established nanofabrication processes for nitride materials and provided a cornerstone for achieving significant enhancement in quantum efficiency of UV emitters through chip-scale integration/architecture. These solid-state UV emitters will find applications in next generation solid-state lighting, fluorescence detection of chemical and biological agents, and in the use of compact UV sources for medical and health research. Nitride PCs are the first of their kind being active in the UV and visible spectral regions and will open up new opportunities for exploring new physics and phenomena.

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### *Kansas State University*


## *Achieved High Al-Content $Al_xGa_{1-x}N$ Alloys with Record Low Resistivity*

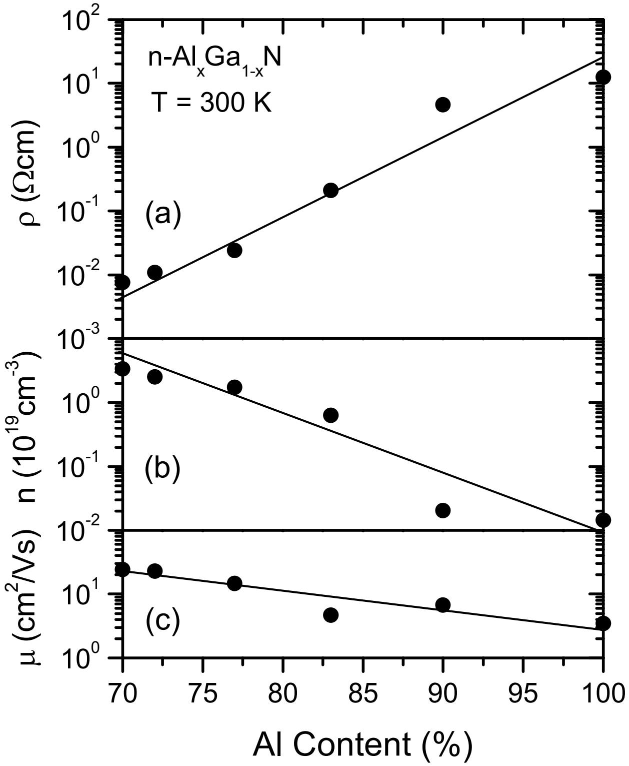
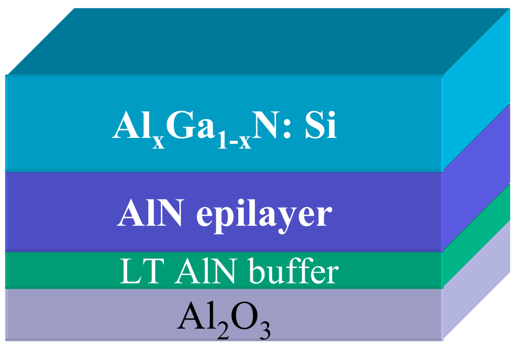



Fig. 1 Room temperature Hall measurement results of n-$Al_xGa_{1-x}N$ ($x \geq 0.7$). (a), (b) and (c) show the Al content (x) dependent resistivity, electron concentration, and electron mobility, respectively.

## Layer structures




**For $Al_{0.7}Ga_{0.3}N$**
**$\rho$= 0.0075 Ω cm**
**n=3.3 × $10^{19}$ $cm^{-3}$**
**$\mu$= 25 $cm^2$/Vs**

Fig. 2 The layer structure of n-$Al_xGa_{1-x}N$ epilayers.

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• We have achieved epitaxial growth of n-type $Al_xGa_{1-x}N$ ($x \geq 0.7$) epilayers with record low resistivities (Fig. 1). For instant, a record low resistivity of 0.0075 Ω·cm has been obtained for Si doped $Al_{0.7}Ga_{0.3}N$ at room temperature. Our success is largely attributed to the insertion of a high quality AlN epilayer that serves as a template for the subsequent growth of AlGaN alloys (Fig. 2). The insertion of AlN template greatly reduces the dislocation density and enhances doping efficiency. By incorporating the new growth conditions and device structures, we have improved the performance of deep UV light emitting diodes.

• Transport measurements (Fig. 1) confirmed that we have achieved n-type conduction in pure AlN. The result implies that, for the first time, we will be able to control the conductivity and index of refraction by applying electric field or by carrier injection in AlN - the ultra-high bandgap (6.1 eV) material.

Aim of the project:

Al-rich $Al_xGa_{1-x}N$ alloys ($x > 0.5$), covering wavelengths from 300 to 200 nm, are ideal materials for the development of chip-scale UV light sources/sensors, because AlGaN is the only ultra-wide-bandgap semiconductor system in which the bandgap can be easily engineered through the use of alloying and heterostructure design. However, achieving highly conductive n-type and p-type $Al_xGa_{1-x}N$ alloys with high Al contents ($x > 0.6$) is essential for the realization of high performance practical devices that are active in the deep UV region, since these materials are needed for current injection. There is an urgent need to develop new approaches to further improve material quality with reduced dislocation density and enhanced doping efficiency. Our NSF supported research program aims at addressing the aforementioned issues.

Research results:

Achieving highly conductive $Al_xGa_{1-x}N$ alloys with high Al contents is known to be very challenging. The formation energy of Al vacancy decreases with increasing Al content in AlGaN and Al vacancies are compensating centers in n-type AlGaN. The presence of dislocations can enhance the formation of cation vacancies during the nitride crystal growth. Thus, a high dislocation density generally translates to a reduced conductivity in AlGaN and AlN. Prior to 2002, only insulating $Al_xGa_{1-x}N$ ($x > 0.5$) could be obtained. By inserting a high quality AlN epilayer that serves as a template for the subsequent growth of AlGaN alloys, we have greatly reduced the dislocation density and thereby enhanced the doping efficiency. The improvement is due to the fact that AlN epilayer has a better lattice match with sapphire than GaN and the capability to provide an atomically flat template for subsequent growth of the device structure. Transport measurements have shown that we have achieved record low room temperature n-type resistivities for Al-rich AlGaN alloys by Si-doping. For instant, a record low resistivity of 0.0075 $\Omega\cdot$cm (with an electron concentration of $3.3 \times 10^{19}$ cm$^{-3}$ and mobility of 25 cm$^2$/Vs) has been obtained for $Al_{0.7}Ga_{0.3}N$. By adopting highly conductive n-AlGaN on AlN epilayer (n-AlGaN/AlN) as a template for the subsequent growth of the device structure, we have significantly improved the performance of deep UV LEDs. Our success for obtaining high quality AlN and AlGaN epilayers is largely attributed to our unique capability for monitoring the optical qualities of these layers - the development of the world’s first (and presently only) deep UV (down to 195 nm) picosecond time-resolved optical spectroscopy system that allows us to make picosecond time-resolved photoluminescence measurements of AlN and AlGaN with high Al contents, thus, we can characterize and thereby improve material quality. Because only high-quality semiconductor materials emit predominantly band-edge photoluminescence, the spectra reveal the optical quality of the sample. By minimizing the ratio of the vacancy to band-edge emission intensity by varying the key growth parameters (growth temperature, pressure and V/III ratio), we have achieved high quality AlN and Al-rich AlGaN alloys with record high conductivities. Determining the quality of the material is key to improving the manufacturing process.

Significance of this work:

Efficient solid-state UV light sources/sensors are crucial in many fields of research and development. For instance, protein fluorescence is generally excited by UV light; monitoring changes of intrinsic fluorescence in a protein can provide important information on its structural changes. Thus, the availability of chip-scale UV light sources is expected to open up new opportunities for medical research and health care. Solid-state UV light sources also have applications in water and air purification, equipment/personnel decontamination, and white light generation. The achievement of conductive AlN makes the control of the index of refraction in this ultrahigh bandgap material possible by applying electric field or by carrier injection, which will bring out n properties and applications. We have begun the shipment of sample devices to several medical research institutions for the development of various medical devices utilizing chip-scale deep UV light sources.

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### *Working with Girls Researching Our World (GROW)*

The P.I. (Lin) of this project serves as a faculty advisor for the Woman in Engineering and Science Program (WESP) at Kansas State University. WESP provides outreach, recruitment, and programs for girls and women from middle school through post-graduate levels, to encourage them to consider and persist in careers in science, mathematics and engineering. WESP has helped to conduct an NSF supported Girls Researching Our World (GROW) workshop, which is targeted for 7$^{th}$ and 8$^{th}$ grade girls. The GROW Workshop is a three-day science enhancement activity held on the Kansas State University campus.

- Together with high school science teacher Shirley Unruh, Professor Lin has developed hands–on working activities dealing with "**Light emitting diodes & semiconductor photonics.**" In June 2004, the girls (about 50 of them) had lively discussions on the principle, fabrication, and applications of semiconductor light emitting diodes (LEDs), laser diodes, and other photonic devices. The girls also visited labs for blue LED and laser wafer growth and fabrication. They also injected current into "Wild-Cats – KSU logo" LEDs that glow in blue and purple colors. Finally, the girls were also provided with a package that contains lab grown LEDs, a resistor and a battery so they can demonstrate the operation of LEDs to their classmates and parents when they get home. The approaches were quite successful and exciting. It was a joy to hear the girls say about activities: "*I am actually smarter than I thought;*" "*The workshop increased my I.Q*;" "*It's so cool and my brothers will be so jealous of what I have seen*."
- In order to reach the broader community, Prof. Lin also conducts demonstrations on LEDs, lasers and optical effects in local elementary schools several times a year. The PI's lab also participates in the yearly university open-house showing NSF supported research and III-nitride photonic devices.